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Assessment of economic viability for PV/wind/diesel hybrid energy system in southern Peninsular Malaysia

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ABSTRACT

This paper analyzed the potential implementation of hybrid photovoltaic (PV)/wind turbine/diesel system in southern city of Malaysia, Johor Bahru. HOMER (hybrid optimization model for electric renewable) simulation software was used to determine the technical feasibility of the system and to perform the economical analysis of the system. There were seven different system configurations, namely stand-alone diesel system, hybrid PV–diesel system with and without battery storage element, hybrid wind–diesel system with and without battery storage

element, PV–wind–diesel system with and without storage element, will be studied and analyzed. The simulations will be focused on the net present costs, cost of energy, excess electricity produced and the reduction of CO_2 emission for the given hybrid configurations. At the end of this paper, PV–diesel system with battery storage element, PV–wind–diesel system with battery storage element and the stand-alone diesel system were analyzed based on high price of diesel.

Contents

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1. Introduction

In recent years, the world climate change and global warming issues have been greatly debated by researchers and environmentalists. This is due to the growth of industrialization and world population which results in the increase of electricity demand especially the conventional electricity generation using the natural resources such as oil, gas and coals. This, in turn, contributes to the increasing in the emissions of green house gasses (GHGs), carbon dioxide, (CO_2) that bring hazard to our atmosphere. Therefore, researchers and policy makers start looking for the renewable energies as the alternative to the conventional fossil fuels such as wind, photovoltaic (PV), biomass, and tidal waves. Renewable energies are gaining popularity because these energies are clean and environmental friendly, which may help to mitigate the issue of GHG emissions.

There are many studies and researches carried out by various researchers in the field of renewable energies. For instance, Malik has conducted study to assess the potential of renewable energies in Brunei Darussalam. From the study, the author identified the availability of renewable energies that could be harvested in Brunei [1]. Dalton et al. performed research in the feasibility analysis of renewable energy sources dependent on stand-alone power supplies for small, medium and large scale tourist operations in Australia [2,3]. The criteria of assessment analysis include net present price, renewable factor and payback time. Another research conducted by Himri et al. has reviewed the utilization of renewable energy situation and studied the potential of wind energy in Algeria. The authors intended to make the public aware of energy efficiency and conservation [4,5]. Review of simulation and optimization techniques for configuration of PV generator, wind turbine and diesel generator to generate electricity has been done by Bernal-Agustín et al. [6]. Simulation of off-grid generation for remote villages in Cameroon has been reported in [7], in which the study investigated the suitable alternative for rural electrification in low power consumption in the range of 10–50 kW.

Phuangpornpitak and Kumar have conducted surveys on users' satisfaction on PV hybrid system in rural (island) community and reviewed the overall energy production and system performance of PV hybrid systems in Thailand [8,9]. In Ref. [10], the authors utilized the RETScreen modeling software to predict the energy production, financial feasibility and reduction of GHG emissions for a 10 MW PV plant in Abu Dhabi, United Arab Emirate. A study of feasibility of using various PV systems under hot climatic conditions of Oman has been done by Jubran et al. [11]. The economic assessments about the effect of PV hybrid penetration on cost of electricity (COE) and operational hours of diesel generator were examined by Shaahid and Elhadidy [12,13]. Li et al. [14] described the modeling and optimization of a stand-alone PV system with different battery storage in Shanghai. It has concluded that the PV–fuel cell–battery configuration was the system with the lowest cost and the highest efficiency as compared to either single storage system.

The electrical requirement of Gokceada, Turkey, was analyzed by Demiroren and Yilmaz [15]. HOMER software was used to consider the optimal system configuration of hybrid renewable energy system. From the study, they found out that wind energy system with grid sales according to the grid connected scenario was the best option to be implemented in Gokceada. Arribas et al. [16] installed a PV–wind hybrid system in Soria, Spain, in order to monitor the performance of the hybrid system throughout a year. They concluded that wind technology showed higher performance than other systems. Literature [17] compares the production costs and performance of the PV–wind–diesel system in four different states in Malaysia. The study indicated that PV–diesel generator hybrid system was the best option in Malaysia in terms of economic performance and pollution. The current state of design, operation and control requirement of the PV–wind–diesel system has been reviewed by Nema et al. [18]. They focused on the future developments of this hybrid system, which have the potential to increase the economic attractiveness of the system.

A PV–wind–diesel system was designed by Bernal-Agustín et al. [19] to minimize the total cost of system installation and to reduce the pollutant emissions by using HOMER software. The results demonstrated the practical utility of the designed method used. An economic evaluation on hybrid PV–wind–fuel cell system was performed by Nelson et al. [20] in Pacific Northwest. The cost comparison results show a clear economic advantage of the traditional PV–wind–battery system over the PV–wind–fuel cell system. It indicated that further research should be carried out in fuel cell area. The simulation of a micro-hydro–PV hybrid system for rural electrification was conducted by Kenfack et al. [21] in Batocha River and Metchie River, Cameroon, using HOMER software. The results showed that it might be rewarding to implement a hybrid system in Batocha or in similar remote areas. Ref. [22] introduces the use of micro grids with high content of renewable energy sources for electrification of villages in Senegal. This study describes the relationship between the electrification costs and the paying capability of the communities.

Literature reviews show that many studies have been conducted in different countries such as Europe and Middle East. Yet, only few researches focus on the tropical climate especially in Malaysia. Therefore, in this paper, HOMER (hybrid optimization model for electric renewable) simulation software was used to determine the optimal design of hybrid renewable energy in a southern city of Malaysia, Johor Bahru. HOMER estimates a system's technical feasibility and then performs the economical analysis and ranks the systems according to total net present cost (NPC). Comparisons and analysis of different configurations of stand-alone hybrid renewable energy systems will be discussed in the following sections. These configurations include the stand-alone diesel system, hybrid PV–diesel system with and without battery storage element, hybrid wind–diesel system with and without battery storage, PV–wind–diesel system with and without battery storage element. The results and discussion reviewed that PV/wind/diesel system with battery is the best option for Johor Bahru in order to reduce the utilization of fossil fuels.

2. Description of input parameters

HOMER simulation software requires some input parameters in order to calculate the optimization results for different configurations of systems. These input parameters are primary load inputs, solar resource input, wind resource input, capacity of power generated, initial costs per unit for each different components. All these parameters will be further elaborated in the following sub-section.

2.1. Building load profile

In this study, a building of four storeys in the Faculty of Electrical Engineering (FKE), Universiti Technologi Malaysia (UTM), was selected to test the feasibility of the designed hybrid renewable

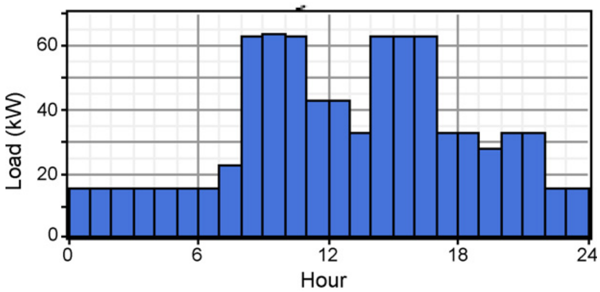

Fig. 1. A sample of the daily load profile for the studied building at FKE, UTM.

energy system. The building consists of five laboratories, six lecture rooms, ten offices and four restrooms. In general, the energy consumption of this building is mainly governed by electricity to power the air-conditioning, lighting, computers and laboratory equipment.

A typical sample of the daily load profile during working day of the building is shown in Fig. 1. The building requires a maximum of 62.5 kW peak demand and it has a base demand of approximately 16 kW. From the load profile, it can be seen that, during night times, the load requirements are the lowest since that is the off working hours of the staffs and students. The maximum demand occurs during daytime from 8 a.m. to 5 p.m. as this is the working hour period. The peak demand is about 62 kW from 8 a.m. to 11 a.m. and 2 p.m. to 5 p.m. where it is the time for students to conduct experiments in the laboratory. The load demand drops to about 42 kW in the afternoon when there are no experiments in the laboratory and therefore the computers and other laboratory equipment were turned off. Usually, some replacement lectures and classes will be conducted by lecturers after working hours, 5 p.m.–10 p.m. and it results in the load demand of about 32 kW. Fig. 2 illustrates the average and the deviation of the monthly load profile for the studied building. It can be noticed that the lowest load demand occurs in May, June and December because these three months are the semester holidays of the university. A random variability is given by HOMER software to estimate the maximum and minimum variations of the daily load profile. This random variability is day-to-day variability and the time-step-to-time-step variability, which is set to be 5% in this study. The scaled annual average energy demand of the studied building as simulated by HOMER software is 763 kWh/day which is equivalent to 278.495 MWh/year.

2.2. Solar radiation

The solar radiation data was obtained from National Aeronautics and Space Administrative, NASA [23]. It is a 22-year average monthly solar radiation data. Fig. 3 shows the solar radiation data inputs as used in HOMER software, on the right axis of which is the clearness index of the solar irradiation. The latitude and longitude of Johor Bahru are 1°28′N and 103°45′E, respectively. The solar radiation ranges from 4.07 kWh/m^2/day to 5.22 kWh/m^2/day. The annual average of solar irradiance is estimated to be 4.56 kWh/m^2/day. It is noticed that solar irradiance

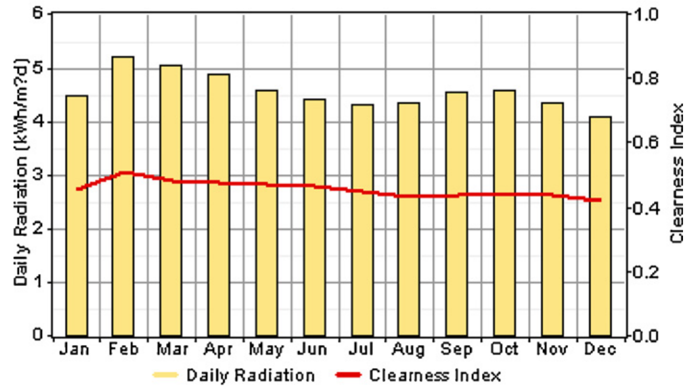

Fig. 3. The annual solar radiation and the clearness index for the location of Johor Bahru, Malaysia.

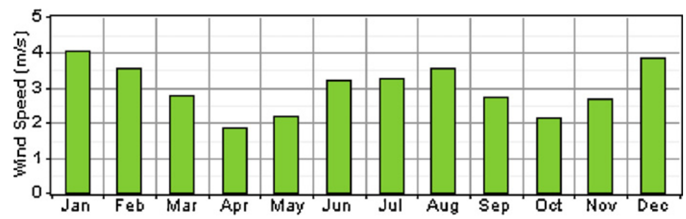

Fig. 4. The monthly wind speed data in Johor Bahru, Malaysia, which is obtained from NASA.

is high for September, October, February and March, while solar irradiance is low from June to August. The low solar irradiation is because of the South-West Monsoon season during this period. The clearness index is automatically generated by HOMER when the daily radiation data is entered [24].

2.3. Wind speed

The wind speed data is obtained from NASA database for the location of Johor Bahru, Malaysia [23]. It is a 22-year average monthly wind speed data measured at 50 m above the surface of sea level in the interval of 3 h as depicted in Fig. 4. The figure shows that the wind speed ranges from 1.9 m/s to 4 m/s. The highest wind speed occurs in December–February and also in June–August, all of which fall under the Monsoon season.

The parameter Weibull *k*, is a measure of long term distribution of wind speed over the year, while the auto-correlation factor is another measure of hour-to-hour randomness of the wind speed, and the diurnal pattern strength is a measure of how strongly the wind speed depends on the time of the day [25]. A low value of *k* corresponds to a broad wind speed distribution, while a high value of *k* shows that the wind speed varies over a narrower range. A low value of auto-correlation factor (0.7–0.8) is in the area of complex topology, while a high value of auto-correlation factor (0.9–0.97) is in the area of uniform topology. Meanwhile, a high value of the diurnal pattern strength shows that there is a relatively strong

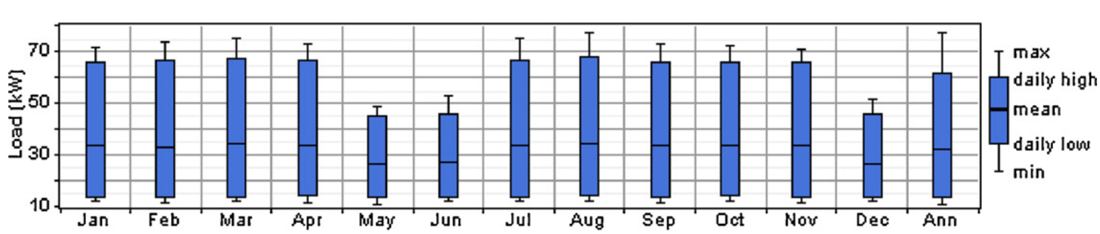

Fig. 2. The variations of the monthly load profiles for the studied building at FKE, UTM.

Table 1
Economic and technical specification for the components of the proposed hybrid energy system.

Description	Specification
1. PV modules	
PV model	PV-MF100EC4
Power (kW peak)	40, 60, 80 kW
Capital cost [28]	$7300/kWh or RM 22,600.80/kWh
Replacement cost [28]	$7300/kWh or RM 22,600.80/kWh
Operating and maintenance cost	$10/year or RM 30.96/year
Lifetime	25 years
2. Wind turbine	
Type of wind turbine	BWC Excel-S
Rated power	10 kW AC
Capital cost [29]	$30,730 or RM 95,140.08 includes Guyed-lattice tower kit and tower wiring kit
Replacement cost [29]	$22,900 or RM 70,898.40
Operating and maintenance cost	$992/year or RM 3071.23
Lifetime	25 years
3. Storage battery	
Type of battery	Surrette 6CS25P
Capital cost [30]	$1229 or RM 3804.98 per single cell
Replacement cost [30]	$1229 or RM 3804.98 per single cell
Operating and maintenance cost	$10/year or RM 30.96/year
4. Inverter	
Inverter model	Solectria PVI-80kW-480V (AC)
Rated power	80 kW
Capital cost [31]	$655/kW or RM 2027.88/kW
Replacement cost [31]	$655/kW or RM 2027.88/kW
Operating and maintenance cost	$10/year or RM 30.96/year
Lifetime	15 years
Conversion efficiency	95%
5. Diesel generator	
Generator model	Cummins Generator
Rated power	80 kW
Capital cost [32]	$225 or RM 696.60
Replacement cost [32]	$180 or RM 557.28
Operating and maintenance cost	$0.030/h or RM 0.093/h
Lifetime	15,000 operating hours
Minimum load ratio	30%

dependence on the time of day and vice versa [15]. In this study, the Weibull parameter (k), the auto-correlation factor and the diurnal pattern strength are assumed to be 1.94, 0.9 and 0.3 respectively.

The hour of peak wind speed is the time of the day that tends to be windiest, on average [25]. From the data provided by NASA, 16:00 hrs is the time where the wind speed is the highest on average.

2.4. Diesel

The latest diesel price in Malaysia is RM 1.75/L [26,27]. Since the Malaysian government will cut the subsidy on diesel and petrol, it means the diesel prices will vary extensively, in which it may be raised up to RM 7.00 or $2.25/L (the currency exchange rate is due to the trade currency of December 2010). Therefore, the diesel price is varied in this simulation to investigate its effect on the system cost.

3. System description and specification

The hybrid PV–wind–diesel system consists of five main components which include a generator, PV modules, wind turbines, batteries and power conditioning units (converters) as shown in Fig. 5(a). Fig. 5(b) shows the configuration of the hybrid energy system which consists of a generator, a PV array, a wind turbine, an inverter and a battery bank, as simulated in HOMER. Table 1 shows the descriptions of the selected components. The design specification for each component is provided in the following section. The HOMER software simulates the system costs based on US dollar, the costs of every component will then be converted to Ringgit Malaysia based on the trade currency of December 2010, US $1 equivalents to RM 3.096.

Table 2
Technical characteristics of BWC Excel-S wind turbine [29].

Start-up wind speed	3.4 m/s (7.5 mph)
Cut-in wind speed	3.1 m/s (7 mph)
Rated wind speed	13.8 m/s (31 mph)
Rated power	10 kW
Furling wind speed	15.6 m/s (35 mph)
Maximum design wind speed	54 m/s (120 mph)
Number of rotor blades	3
Rotor diameter	7 m (23 ft)
Hub heights	18 m (60 ft) to 37 m (120 ft) (20 m is used for simulation)

3.1. Sizing of the PV modules

In this study, in order to fulfill the basic load demand of the studied building, the PV array size was set at 80 kW_p. This PV size would be enough to provide the peak building demand of approximately 77 kW. In any case of excess PV yield energy, the excess energy would be used to charge the battery storage. Since the hybrid system is the combination of PV and wind power, the size of the PV is varied from 40 kW_p and 80 kW_p with an interval of 20 kW_p, in order to examine the impact of the financial costing of the hybrid system. The selected PV module is a 36-cell polycrystalline (PV-MF100EC4) which is rated at 100 W_p [28]. There are 800 PV modules connected in series in order to generate 80 kW_p, in which the area of each module is 0.81 m^2, which yields a total area of 648 m^2.

Since the PV module converts the sunlight into electricity, it is impossible to harvest PV energy throughout a day. In general, in Malaysia, the average duration of daytime is approximately 6.97–8.47 h. Therefore, hybrid system of batteries, wind turbines and/or generators is typically combined with PV to take over the energy supply at night.

Derating factor is a scaling factor which is applied to the PV array power output to compensate the reduction in PV module efficiency [25]. In this simulation, the derating factor is assumed to be 90%. The PV modules is less efficient when the temperature increases [14,18], hence, the effect of temperature is taken into account in this simulation. The temperature coefficient is −0.5%/°C, where the modules produce 0.5% less power for the increase of 1 °C in temperature. The nominal operating temperature of the PV module is at 47.5 °C in which the efficiency under standard test condition is 11.9% [28].

3.2. Wind turbine – generation and characteristics

In this simulation, the model BWC Excel-S, 10 kW (AC) type wind turbine was chosen [29]. Table 2 shows the technical characteristics of the wind turbine. For the purpose of economic assessment, the operating and maintenance cost is assumed to be 3%. Fig. 6 shows the power–speed characteristic of the wind turbine generated using HOMER.

3.3. Storage battery

The model Surrette 6CS25P [30] battery was chosen as the storage element in this simulation. The characteristics of the battery are shown in Table 3. In order to produce higher energy capacity, batteries are connected in series, which form battery string that consists of 10 batteries in each string. Each string of battery is capable of producing 70 kWh of electricity. Number of battery strings is varied from 1 to 10 strings to assess the performance of energy and

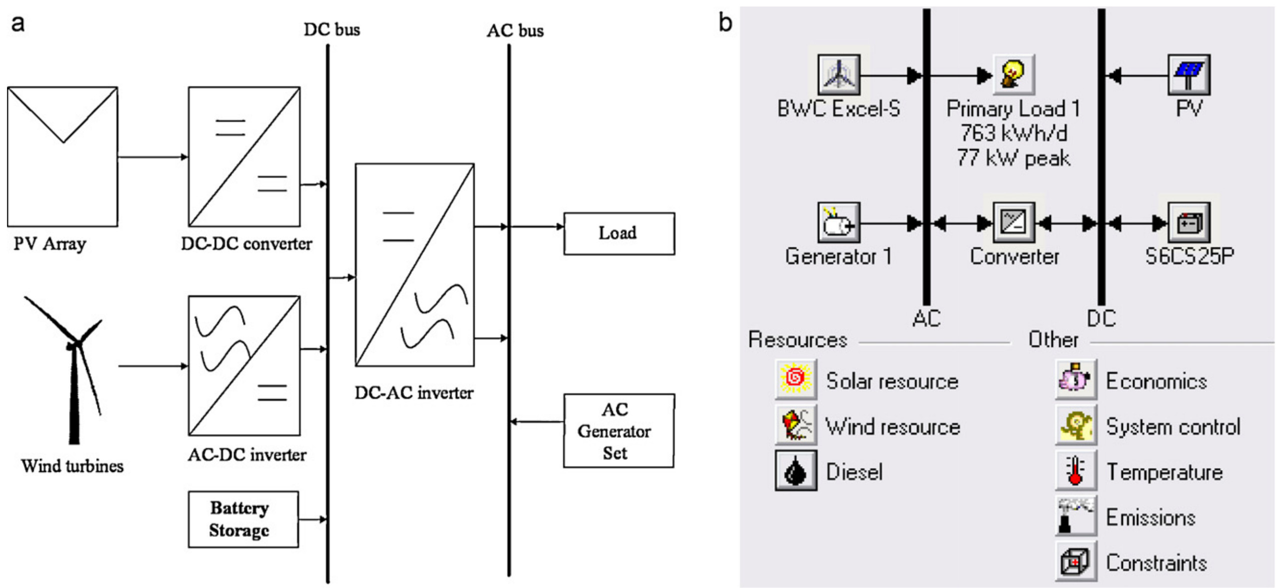

Fig. 5. (a) A block diagram of the proposed hybrid PV–wind–diesel with battery energy system. (b) The configuration of hybrid PV–wind–diesel system as designed in HOMER simulation software.

Table 3
Characteristics of Surrette 6CS25P battery [30].

Nominal capacity	1156 Ah (6.94 kW)
Nominal voltage	6 V
Round trip efficiency	80%
Minimum state of charge	40%
Float life	12 years
Maximum charge rate	1 A/Ah
Maximum charge current	41 A
Lifetime throughput	9645 kWh

demand flow in the case if PV does not produce energy at night and/or if there is no wind to rotate the wind turbine.

4. Operating strategies

The proposed hybrid energy system is assumed to operate according to load following dispatch strategy. Under this strategy, only PV modules and wind turbines will charge the battery storage element. The generator produces only enough power to meet the load demand. Hence, load following dispatch strategy tends to be optimal in system with multiple renewable energies. This strategy may help to reduce the total NPC of the system and to reduce excess electricity produced because the excess electricity produced is used to charge the battery storage element [19].

The PV modules produced DC power, which later needs to be converted into AC source using an inverter. The PV and wind turbine will charge the battery storage element when there is excess energy after meeting the load demand. Based on the wind speed data, afternoon time tends to be windier as compared to morning time. Wind turbine can always produce power to the system whenever the PV is not able to meet the entire load demand. In the worst case, if both PV and wind energy are not enough to meet the demand, the battery will discharge to cater the demand. The generator will only operate if all of the energy sources fail to meet the load demand which typically happens during night time.

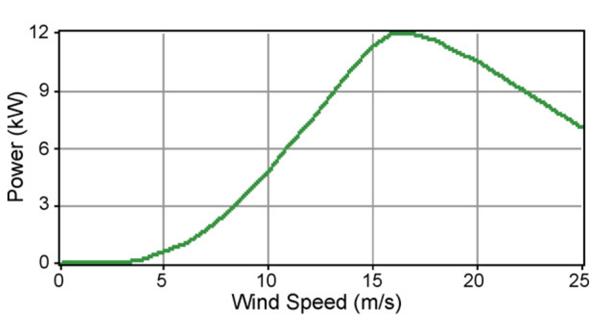

Fig. 6. The power–speed characteristic curve of BWC Excel-S wind turbine.

In HOMER simulation, the operating reserve, as a percent of hourly load is set to be 10%; while the operating reserve, as a percent of solar power output and wind power output are set to be 25% and 50%, respectively. The operating reserve is the surplus operating capacity that ensures reliable electricity supply even if the load suddenly increases or renewable power output suddenly decreases [24]. For example, if the energy required is 80 kWh and the PV output yield is only 30 kWh while the energy generated from wind turbine is only 30 kWh; then the operating reserve can be calculated as follows:

$$\text{Operating reserve} = (\%_L \times E_L) + (\%_{PV} \times E_{PV}) + (\%_{WT} \times E_{WT}) \quad (1)$$

where $\%_L$ is the percent of hourly load, $\%_{PV}$ is the percent of solar power output, $\%_{WT}$ is the percent of wind power output, E_L is the energy required by the load, E_{PV} is the energy generated by PV modules, and E_{WT} is the energy generated by wind turbine.

From Eq. (1), it means that the diesel generator should provide 20 kWh of electricity (the deficit energy after deducting PV and wind) with an extra of 30.5 kWh of operating reserve.

5. Economic analysis

The economic input parameters are needed for HOMER simulation, these parameters include annual real interest rate and project lifetime. After simulation was performed, HOMER ranks all systems according to total net present cost. Besides that, the levelized cost of energy might be taken into account to obtain the optimal results of different system configurations because it is another convenient metric for comparison. All these economic parameters will be discussed in the following sections.

5.1. Annual real interest rate

The annual real interest rate is the discount rate which is used to convert between one-time costs and annualized costs. It is calculated based on Eq. (2).

$$\text{Annual real interest rate, } i = \frac{i' - f}{1 + f} \quad (2)$$

From Eq. (2), i is the real interest rate, i' is the nominal interest rate and f is the annual inflation rate. In Malaysia, the nominal interest rate and the annual inflation rate as referred in November 2010, are 2.75% and 1.90%. Therefore, the annual real interest rate of 0.83% was used in this simulation [33].

5.2. Net present cost (NPC)

The net present cost is the present value of installing and operating the system over its lifetime in the project, it is referred to lifecycle cost. The optimization results of HOMER simulation are ranked and based on the total NPC which is calculated according to Eqs. (3) and (4).

$$C_{\text{NPC}} = \frac{C_{\text{ann,tot}}}{\text{CRF}(i, N)} \quad (3)$$

$$\text{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (4)$$

In the above equations, $C_{\text{ann,tot}}$ is the total annualized cost (\$/year) which includes capital, replacement, annual operating and maintenance, and fuel costs. CRF is the capital recovery factor which is a ratio used to calculate the present value of a series of equal annual cash flows, i is the real interest rate (%) and N is the project lifetime (in year).

5.3. Levelized cost of energy (COE)

Levelized cost of energy is the average cost per kilowatt hour (\$/kWh) of useful electrical energy produced by the system. It is calculated as follows:

$$\text{COE} = \frac{C_{\text{ann,tot}}}{E_{\text{prim,AC}} + E_{\text{prim,DC}}} \quad (5)$$

In this equation, $C_{\text{ann,tot}}$ is the total annualized cost (\$/year), $E_{\text{prim,AC}}$ is the AC primary load served (278,495 kWh/year) and $E_{\text{prim,DC}}$ is the DC primary load served (kWh/year).

6. Results and discussion

The simulation was performed by comparing the optimal configurations of stand-alone diesel system, hybrid PV/diesel system with and without battery storage element, wind/diesel system with and without battery storage element, and PV/wind/diesel system with and without battery storage element (Fig. 7). The simulation was done with a project lifetime of 25 years. The PV capacity is varied for 0, 40, 60 and 80 kW. The wind turbine is varied from 1 turbine to 8 turbines, while the battery storage element varied from 10 units to 100 units.

6.1. Stand-alone diesel system

The stand-alone diesel system is the cheapest system among the studied configurations, with total net present cost (NPC) of RM 8,484,458 based on the diesel price of RM 1.75/L. The levelized cost of energy (COE) for diesel only system is RM 1.353/kWh. The AC load is the annual average electricity demand, which requires 278,495 kWh of electricity/year. In this system, the diesel generator could produce 310,206 kWh of electricity/year, with 31,711 kWh/year or 10.2% of excess electricity. The carbon dioxide, CO_2 emission is 351,844 kg/year. According to David Biello [34], when a trillion tons of carbon was released into the atmosphere, it may cause a peak warming of 2 °C, it is identified as the danger point. Therefore, the world has to keep the carbon level below a trillion tons in order to limit the effect of global warming. Fig. 8 shows the cash flow summary of the system which is analyzed by different cost types. It can be noticed that the main expenses of the system was the fuel consumption, followed by operating and maintenance cost of the system. It means that a lot of money is spent on the fuel consumption, operating and maintenance of the system in order to sustain its function once it was installed.

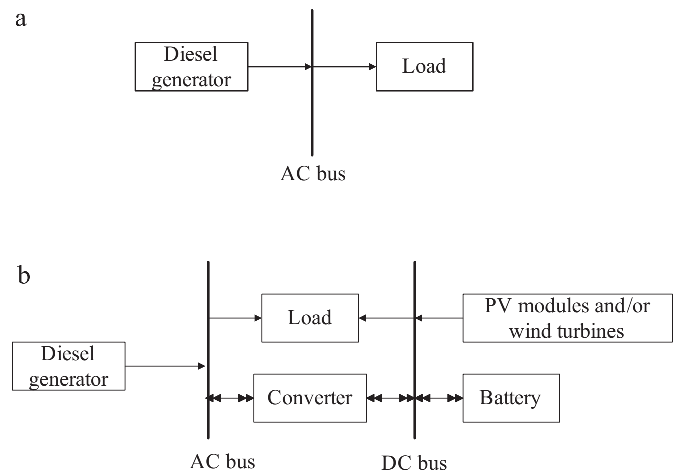

Fig. 7. The block diagrams of mode description for (a) stand-alone diesel system and (b) hybrid renewable energy system.

6.2. Hybrid PV/diesel system without battery storage

Fig. 9(a) shows the graph plotted for net present cost (NPC) and cost of energy (COE) of the system, while Fig. 9(b) shows the graph of the excess electricity produced by the hybrid system and the reduction of CO_2 emission against three different PV capacities of 40 kW, 60 kW and 80 kW. It can be noticed that the NPC values and COE values increase as the capacity of PV increases from 40 kW to 80 kW. This is because the initial cost of PV modules increases linearly with the PV capacity. The greater the PV capacity, the higher the initial cost of PV modules. The excess electricity produced by PV modules and the reduction of CO_2 emission also increase with the increase of PV capacity. The greater the PV capacity, the greater the

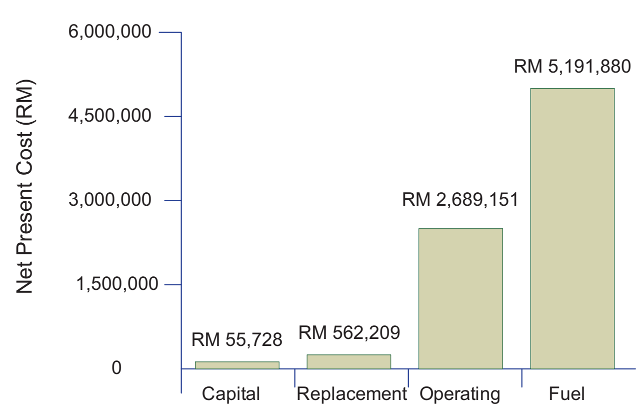

Fig. 8. Summary of cash flow (net present cost) for stand-alone system according to its cost breakdown.

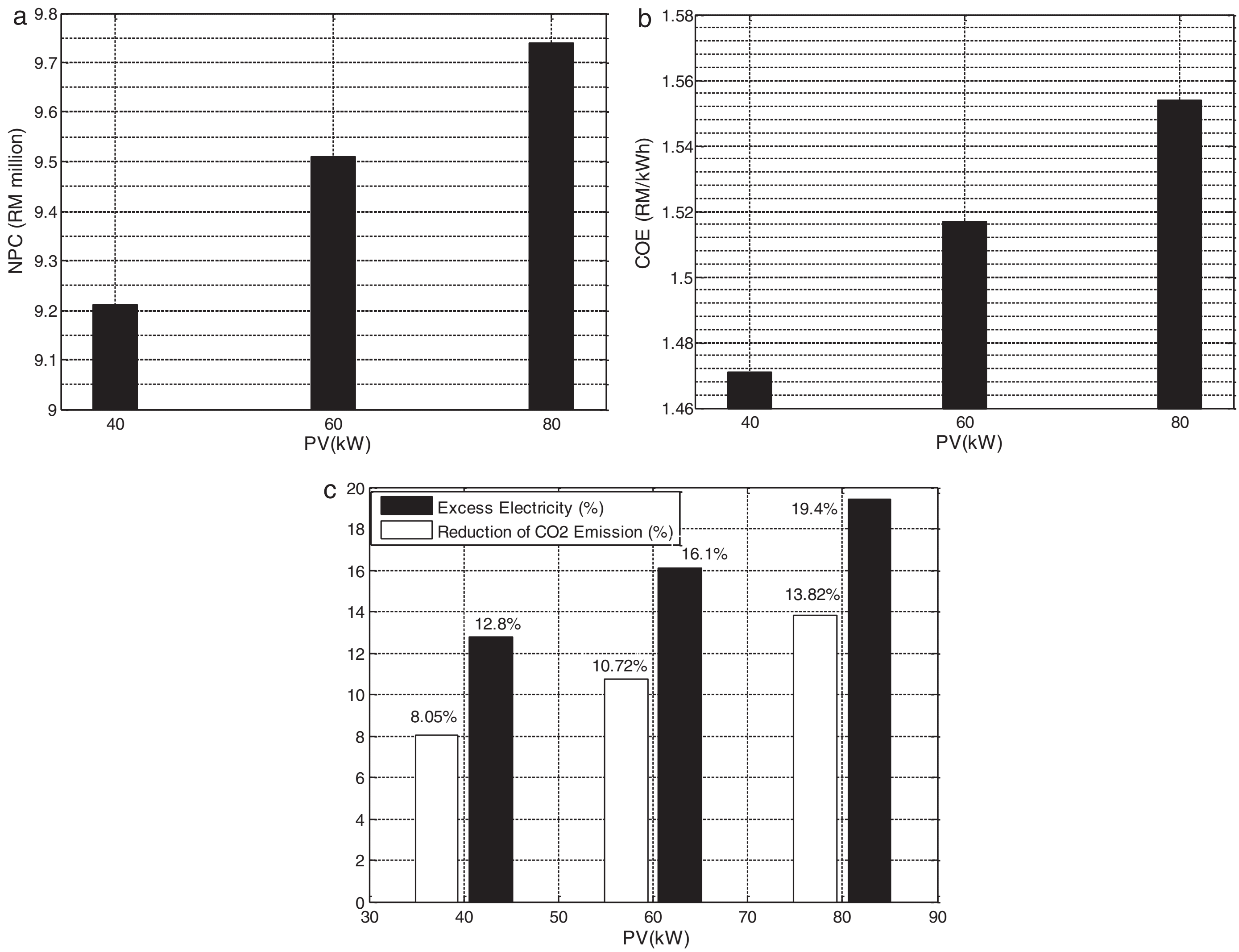

Fig. 9. Simulation results for the PV–diesel system without battery: (a) the NPC values as a function of the PV capacity, (b) COE values as a function of the PV capacity, and (c) the excess electricity produced by PV modules and the reduction of CO_2 emission against the PV capacity.

amount of electricity generated by the PV modules during daytime. When the electricity produced by the PV modules exceeds the load demand, there is excess electricity which is wasted since there is no battery storage in the system to store the excess electricity. The hybrid PV/diesel system released about 303,229–323,504 kg/year of CO_2 gas for different PV capacities. Fig. 9(b) indicates that less CO_2 emission occurs for greater capacity of PV. The reduction of CO_2 emission is compared to the amount of CO_2 released in the stand-alone diesel system, which is about 351,844 kg/year. In this hybrid PV–diesel system, the percentage of reduction of CO_2 emission ranges from 8 to 14%. It means that at least 28–49 tons of CO_2 gas can be avoided to be released into the atmosphere every year.

Table 4 shows the percentage of PV penetration into the system, the electricity productions by the PV modules and the whole system respectively. The PV energy productions and PV penetration for the same capacity PV systems will be the same throughout all of the simulations. Therefore, they will not be mentioned for the following results of other hybrid systems.

6.3. Hybrid PV/diesel system with battery

Fig. 10(a) shows the NPC values of three different PV capacities against number of battery. It can be noticed that the NPC values decrease from 10 units to 30 units battery, then the NPC values increase from 40 units to 100 units battery. The NPC value of 40 kW PV system with 30 units battery is the lowest among the simulations, it is about RM 8.66 million. While the NPC values of 60 kW PV system with 30 units battery and 80 kW PV with 40 units battery are RM 8.75 million and RM 8.68 million respectively. The net present cost of the simulation greatly depends on the total annualized cost of each component in the system. It means that different system configurations will provide different variations of NPC values against different numbers of battery.

The graph of the COE values as a function of the number of battery is shown in Fig. 10(b). It can be noticed that the pattern of the graph is quite the same as that of NPC graph. It is because the COE values are directly proportional to total annualized cost of the system, which means it is also directly related to the NPC values, therefore the graph generated is in the same pattern. The highest COE is about RM 1.505/kWh for 80 kW PV with 10 units battery, while the lowest COE is about RM 1.384/kWh for 80 kW PV with 40 units battery.

The graph of excess electricity generated by the PV system against number of battery for three different PV capacities is shown in Fig. 10(c). The percentage of excess electricity produced by the PV system decreases with the increasing number of battery, it ranges from 0 to 14%. For any capacity of PV with 60–100 units battery, the excess electricity produced is the lowest, which is less than 2%. This

Table 4
Energy yield in the hybrid PV/diesel system without battery.

PV (kW)	Percentage of the PV penetration into the system (%)	PV production (kWh/year)	Total electricity production of the system (kWh/year)
40	19.6	54,684	321,849
60	29.5	82,026	335,429
80	39.3	109,368	349,885

means that a lot of energy can be saved and stored for utilization for the system with greater number of battery.

Fig. 10(d) shows the graph of reduction of CO_2 emission against number of battery. The percentage of reduction of CO_2 emission increases with the increase number of battery for all PV capacities. The reduction of CO_2 emission for 80 kW PV is the greatest, it ranges from 19 to 32%. In another word, 19–32% of the fuels utilization can be reduced too.

Based on HOMER simulation results, 80 kW of PV/diesel system with 40 units battery is the best configuration because the NPC and the COE values are the lowest, which are RM 8,749,813 and RM 1.384/kWh respectively. These values are RM 265,355 and RM 0.031/kWh respectively greater than those of stand-alone diesel system. This hybrid system can reduce the excess electricity produced from 10.2% to 2.8% where it reduces a lot of wasted energy. The reduction of CO_2 emission is about 30%, which indicates that 30% of fuels are saved for the system.

Fig. 11 shows the summary of cash flow for the hybrid PV–diesel system with 80 kW PV and 40 units battery. The capital cost of the system is RM 2,178,222, it is about RM 2,122,494 greater than the capital cost of stand-alone diesel system. This is due to the high initial cost of PV modules. Since, about 63.7% of total electricity was produced by the diesel generator, it results in high NPC value for the fuel consumption. Although the NPC value for the fuel consumption is the highest in the system, yet 30% or RM 1,569,640 of the NPC value was reduced as compared to stand-alone diesel system.

6.4. Hybrid wind/diesel system without battery

Fig. 12(a) shows the graph of NPC and COE values against the number of wind turbine. Both NPC and COE values increase with the increasing number of wind turbine. The NPC values range from about RM 8.66 million to RM 9.97 million while the COE values range from about RM 1.384/kWh to RM 1.591/kWh. Fig. 12(b)

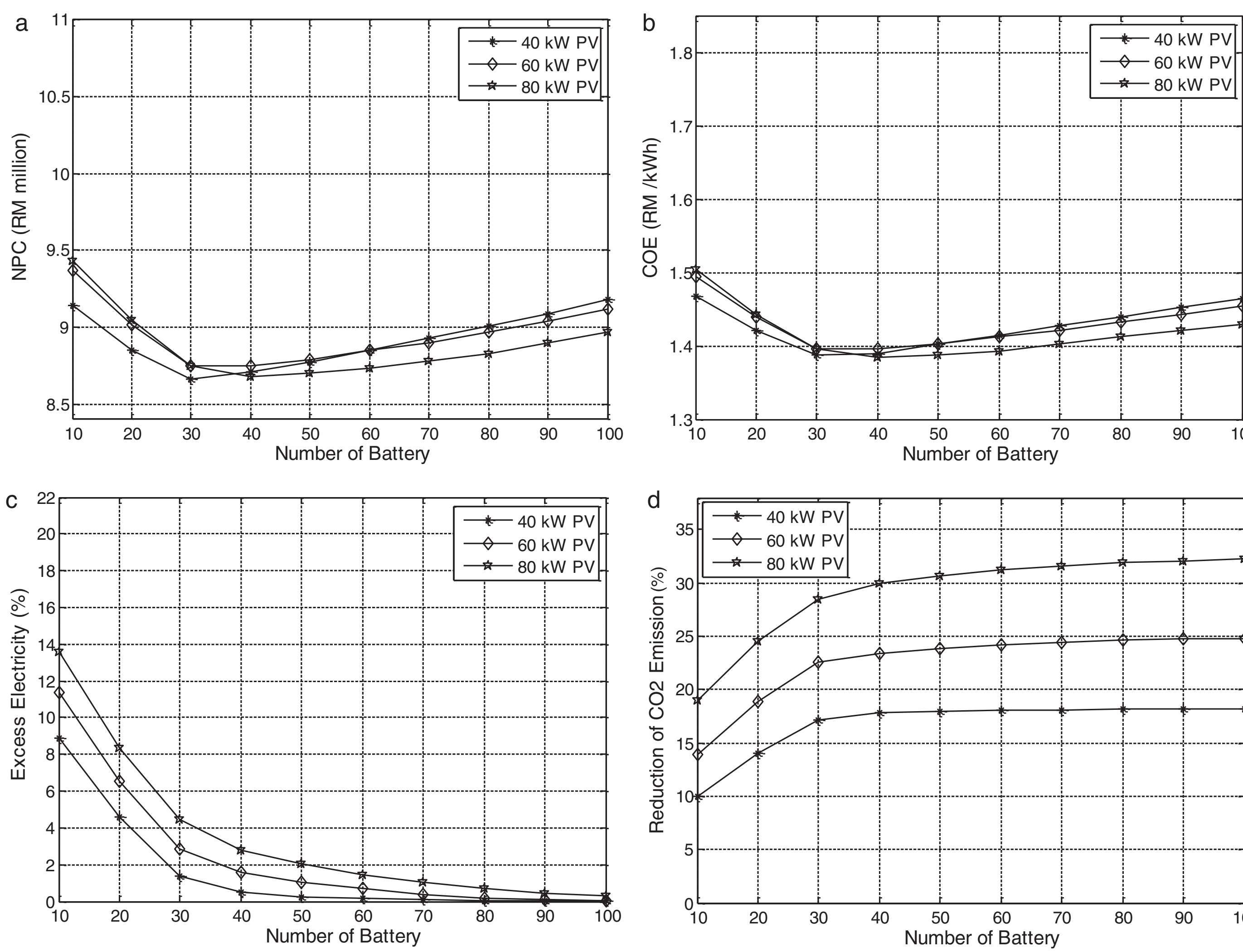

Fig. 10. Simulation results for the hybrid PV–diesel system with battery: (a) NPC values, (b) COE values, (c) the excess electricity produced by the system and (d) the reduction of CO_2 emission against the number of battery for three different PV capacities (40 kW, 60 kW and 80 kW).

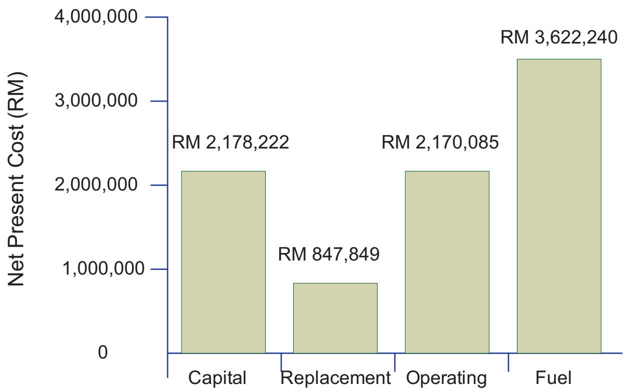

Fig. 11. The summary of the cash flow (net present cost) for the hybrid PV/diesel system with 80 kW PV and 40 units battery.

shows the graph of excess electricity produced by wind turbine and reduction of CO_2 emission against the number of wind turbine. The percentage of excess electricity produced by wind turbines is very high, it ranges from 10.4 to 11.9%, which is slightly higher than the excess electricity produced by stand-alone diesel system (10.2%). This results in wastage of a lot of electricity since there is no battery storage for the system. The percentage of reduction of CO_2 emission is very low, it is about 0.3–2.1%. It indicates that the hybrid wind–diesel system without battery has less potential in reducing the emission of CO_2 effectively.

6.5. Hybrid wind/diesel system with battery

Fig. 13(a) and (b) shows the graphs of NPC and COE values as a function of the number of battery for various units of wind turbine. It can be noticed that the patterns of the both graphs of NPC and COE values against number of battery are similar to each other. The NPC values and COE values decrease from 10 units to 30 units battery, then these values increase with the increase in the number of battery. At the same time, the NPC and COE values increase with the increase in the number of wind turbine. The greater the number of wind turbine, the greater the capital cost of the system, then the greater the NPC and the COE values of the system. All different units of wind turbine with 30 units battery give the minimum NPC and COE values of the system. Based on the simulation, the NPC values range from about RM 8.56 million to RM 10.26 million, while the COE values range from about RM 1.365/kWh to RM 1.638/kWh.

The graph of excess electricity produced by wind turbine against the number of battery for varied units of wind turbine is shown in Fig. 13(c). The excess electricity produced by the wind turbine is inversely proportional to the number of battery. All different system configurations with number of battery more than 60 units do not produce any excess electricity. The highest excess electricity produced by wind turbine is about 8%, which is 4% less than excess electricity produced by the previous mentioned system, wind–diesel system without battery storage element. The system with greater number of battery could save more electricity.

Fig. 13(d) shows the graph of reduction of CO_2 emission for varied units of wind turbine. Similar to the previous mentioned system, the percentage of reduction of CO_2 emission is directly proportional to the number of battery and the number of wind turbine. The graph shows that the reduction of CO_2 emission ranges from about 2% to 12%. It can be noticed that the percentage of reduction of CO_2 gas is much greater than that of wind–diesel system without battery storage element.

6.6. Hybrid PV/wind/diesel system without battery

Fig. 14(a) and (b) shows the graphs of NPC and COE values against number of wind turbine for PV system with different capacities of 40 kW, 60 kW and 80 kW PV modules. Both the NPC and the COE values increase with the increase in the number of wind turbine and increase in the PV capacity. It can be noticed that the NPC and the COE values are very much higher than those of the stand-alone diesel system. It is because the capital costs of PV modules and wind turbines are very high. Therefore, the greater the PV capacity and the greater the number of wind turbine, then the greater the NPC and the COE values of the hybrid system. The NPC values of the system range from about RM 9.40 million to RM 11.27 million, while the COE values of the system range from about RM 1.502/kWh to RM 1.799/kWh.

The percentages of the excess electricity produced by the hybrid PV–wind–diesel system and the reduction of CO_2 emission increase with the increasing numbers of wind turbine and PV capacity are shown in Fig. 14(c) and (d). There is a lot of excess electricity produced by this hybrid system. About 13–22% of excess electricity was wasted. This amount is very much greater than that of the previous

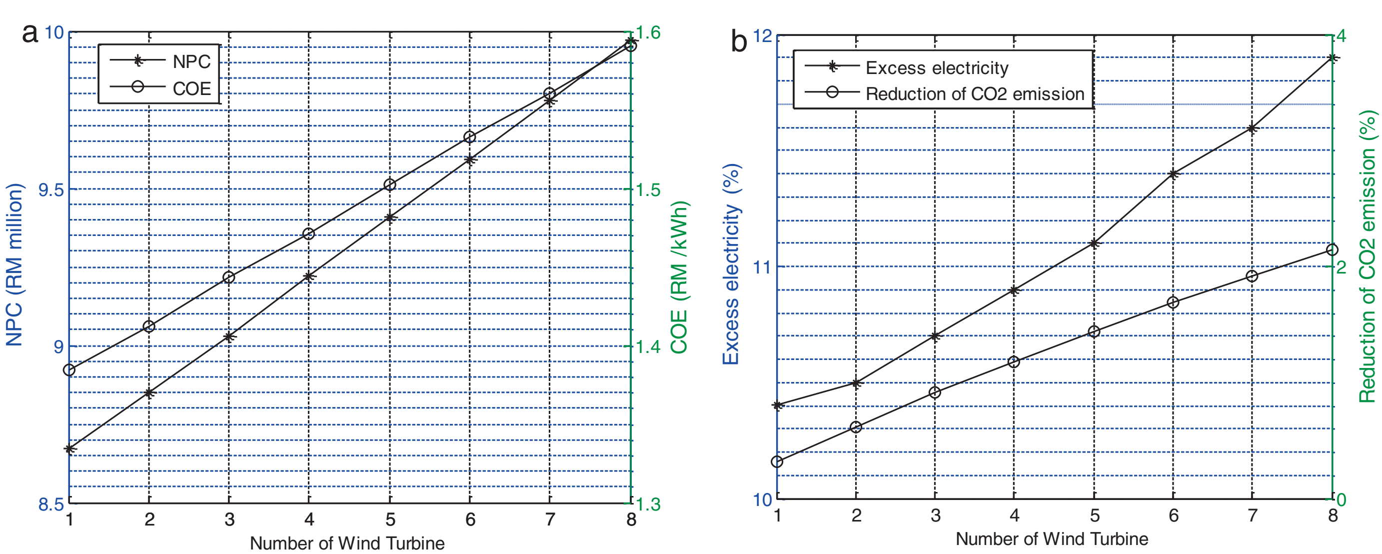

Fig. 12. Simulation results for the wind–diesel systems without battery: (a) the NPC and COE values as a function of the number of wind turbine, and (b) the excess electricity produced by wind turbine and the reduction of CO_2 emission against the number of wind turbine.

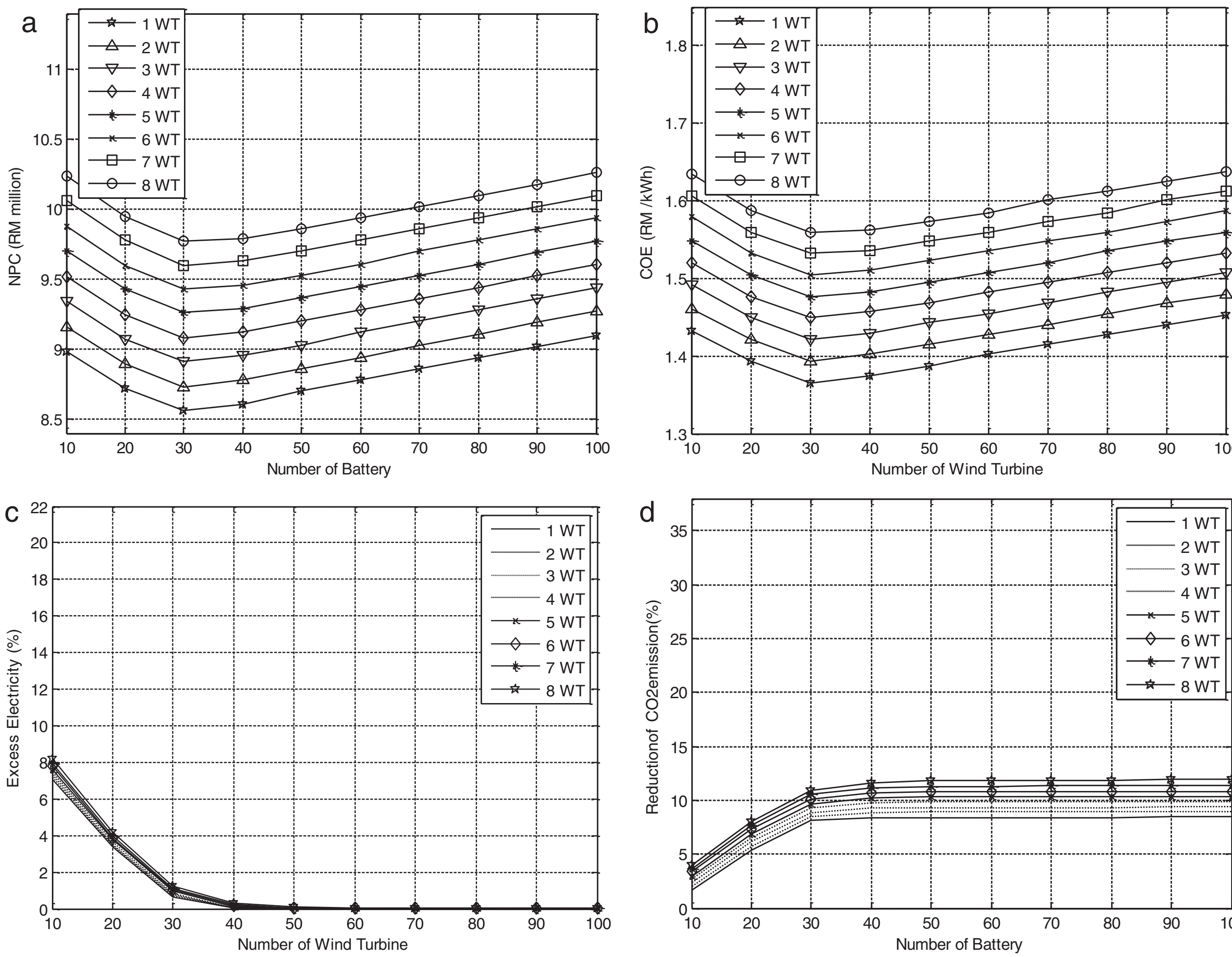

Fig. 13. Simulation results for the wind–diesel system with battery: (a) the NPC values, (b) the COE values, (c) the excess electricity produced by the system, and (d) the reduction of CO_2 emission against the number of battery for varied number of wind turbine (one unit to eight units wind turbine).

mentioned systems because there is no battery storage as a backup to store the excess electricity produced by the wind turbines and PV modules. Meanwhile, this hybrid system can only reduce 8–15% emission of CO_2 gas. Therefore, it is inappropriate to choose this configuration in order to reduce the emission of CO_2 efficiently.

6.7. Hybrid PV/wind/diesel system with battery

Fig. 15(a)–(f) shows the plotted results of the hybrid PV–wind–diesel system with battery. It can be noticed that the NPC value of the 40 kW PV system with 10–30 units battery increases with the increase of battery number, while the system with greater numbers of battery (i.e. 40–100 units), the NPC value increases with the increase of battery number. The NPC values are in the range of RM 8.86 million–RM 10.63 million, whereas the lowest NPC values are at 30 units battery. For the hybrid system with 60 kW_p PV capacity, the graph pattern is similar to that of 80 kW_p PV system, as shown in Fig. 15(b). The NPC values of both systems with 10–40 units battery increase with the increase of battery number, meanwhile the NPC values of both systems with 50–100 units battery increase with the increase of battery number. The range of the NPC values for both 60 kW and 80 kW PV systems is quite the same which is RM 8.83 million–RM 10.84 million. The NPC values are the lowest at 40 units battery for both 60 kW and 80 kW PV systems.

The graph patterns of the COE values against the number of battery for 40 kW, 60 kW and 80 kW PV systems are the same as the graphs of the NPC values against the number of battery for the same systems as shown in Fig. 15(c) and (d). The COE values of all the system configurations are in the range of RM 1.409/kWh–RM 1.731/kWh. The NPC and the COE values of this hybrid system are very much higher than the NPC and COE values of other hybrid systems because the presence of both PV modules and wind turbine in the systems require very high initial costs as compared to the stand-alone systems with either PV modules or wind turbines only.

Fig. 15(e) shows the graph of the excess electricity produced by the PV modules and the wind turbine against the number of battery for 80 kW PV system. When the same kind of graph is plotted for 40 kW and 60 kW PV systems, the graphs show the same patterns as that of 80 kW PV system. The excess electricity produced by PV modules and wind turbines decreases with the number of battery. At the same time, the excess electricity produced increases with the increase of wind turbines and, similarly for the increase of PV capacity. Therefore, the ranges of the excess electricity produced are slightly different for different PV systems: they are 0–11% for 40 kW PV system, 0.2–13.7% for 60 kW PV system and 0.5–15.7% for 80 kW PV system respectively. The greater the PV capacity and the number of wind turbine, the greater

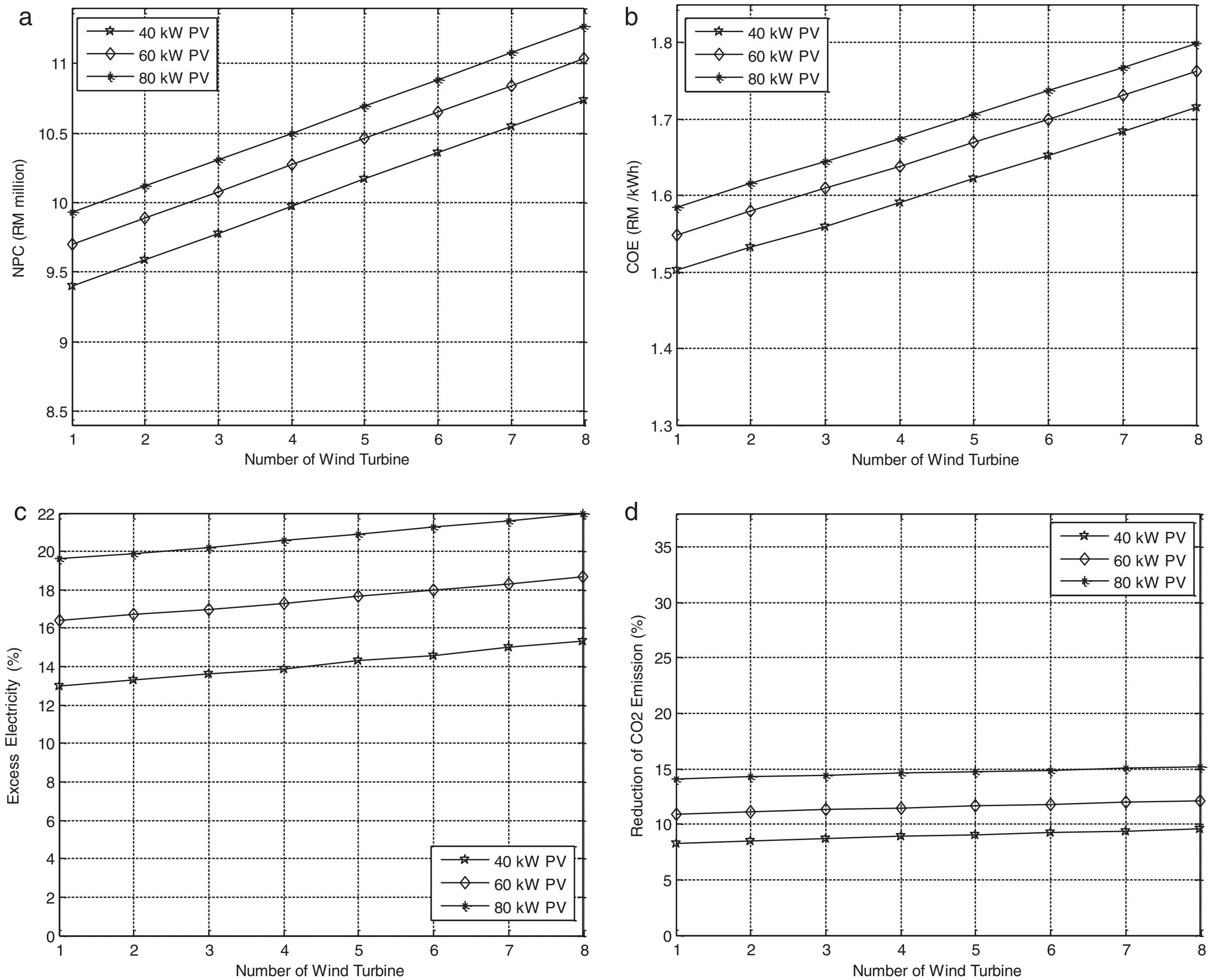

Fig. 14. Simulation results for the hybrid PV–wind–diesel system without battery: (a) the NPC values, (b) the COE values, (c) the excess electricity produced by the PV modules and the wind turbines, and (d) the reduction of CO_2 emission against the number of wind turbine for three different PV capacities (40 kW, 60 kW and 80 kW).

the amount of excess electricity produced by the hybrid system. The greater the number of battery, the lesser the amount of electricity wasted because the larger number of battery is used to store the excess electricity for backup utilization.

Fig. 15(f) shows the graph of the reduction of CO_2 emission against the number of battery for 80 kW PV system. The graphs of CO_2 emission reduction against the number of battery for 40 kW and 60 kW PV systems show the same patterns as the graph of 80 kW PV system. It can be noticed that the greater the number of battery, the higher the percentage of CO_2 emission reduction. The 80 kW PV–wind–diesel system with battery can reduce emission of CO_2 from about 19 to 38%. Meanwhile, the percentage of the reductions of CO_2 emission for 40 kW PV system and 60 kW PV system is about 10.4–22.8% and 14–30% respectively. It indicates that this hybrid system can reduce the emission of CO_2 effectively and it saves a lot of fossil fuels at the same time.

Based on the simulation results, the configuration of PV–wind diesel system with 80 kW PV modules, 8 units wind turbine and 50 units battery is considered to be the best option. The NPC value of this configuration is RM 9,911,051, which is RM 1,426,593 or 16.8% greater than the NPC value of diesel only system. Its COE value is RM 1.582/kWh which is RM 0.229/kWh greater than that of diesel only system. Although, the NPC and the COE values are greater than those of diesel only system, yet it is still considered to be at low cost since it utilizes the renewable energies which are environmental friendly. In addition, it reduces the excess electricity produced from 10.2% (stand-alone diesel system) to 2.61%. It means that excess electricity produced can be stored in the battery as a backup utilization and is not to be wasted. This system is also capable of reducing 34.5% or 124 tons of CO_2 gasses from being emitted into the atmosphere every year. It could work well to save a lot of fossil fuels.

6.8. Simulation results for systems with high price of diesel

Table 5 shows the comparison for three different systems with diesel price of RM 1.75/L and RM 7.00/L. These three systems are diesel only system, PV/diesel system with 80 kW PV and 40 units battery and PV/wind/diesel system with 80 kW PV, 8 units wind turbine and 50 units battery. These systems have been mentioned in previous sections as one of the best choices for hybrid system implementation. Based on Table 5, it can be seen that when diesel price increases four times from RM 1.75/L to RM 7.00/L, the NPC and the COE values of diesel only system increase 2.83

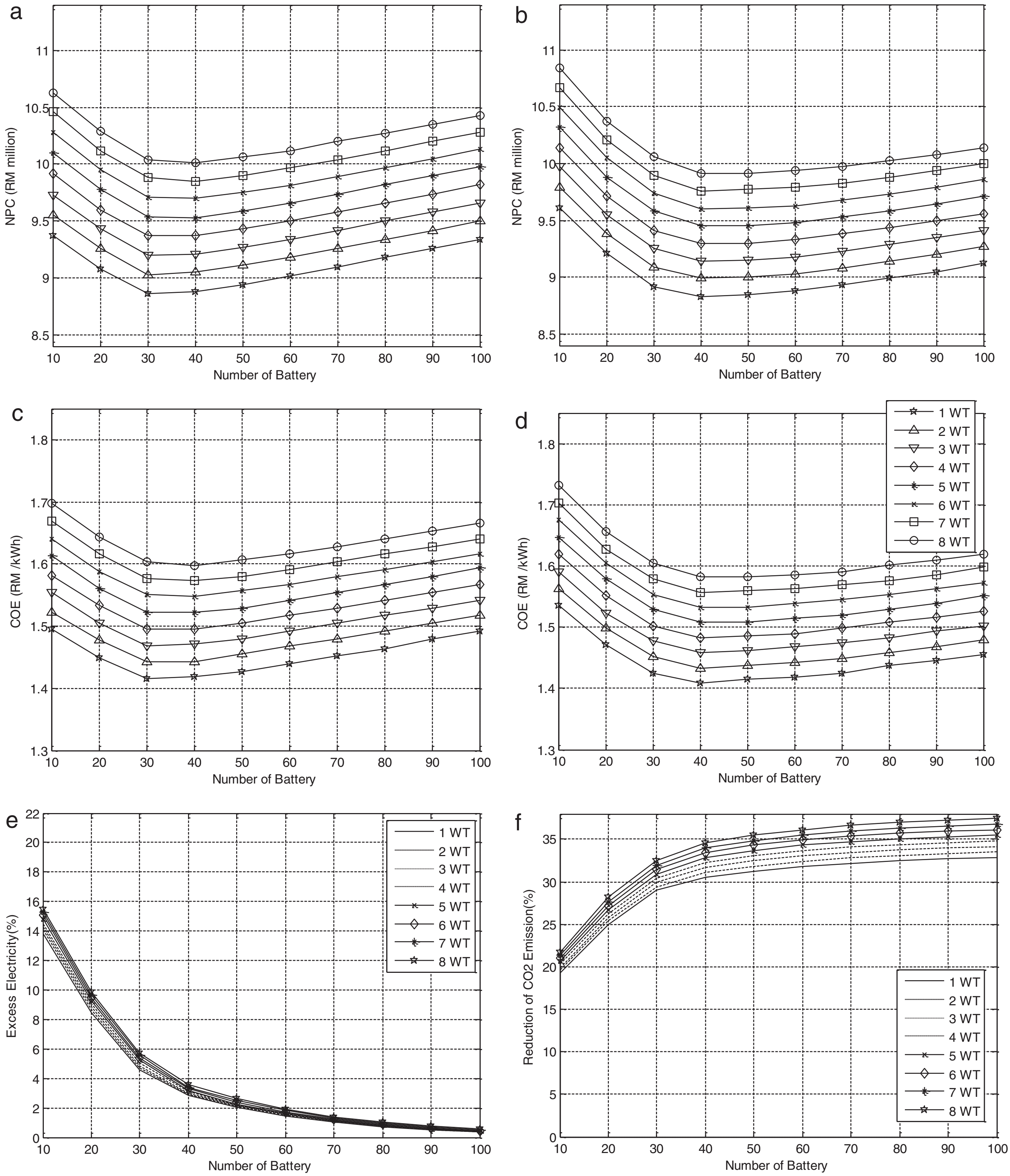

Fig. 15. Simulation results for the hybrid PV–wind–diesel system with battery: (a) the NPC values against the number of battery for 40 kW PV system, (b) the NPC values against the number of battery for 80 kW PV system, (c) the COE values against the number of battery for 40 kW PV system, (d) the COE values against the number of battery for 80 kW PV, (e) the excess electricity produced by the hybrid system, and (f) the reduction of CO_2 emission against the number of battery for 80 kW PV system.

Table 5
The summary of economic costings for the studied systems.

System configuration	Diesel price = RM 1.75/L		Diesel price = RM 7.00/L	
	NPC (RM)	COE (RM/kWh)	NPC (RM)	COE (RM/kWh)
Diesel only system	8,484,458.00	1.353	24,041,486.00	3.839
PV/diesel system with 80 kW PV and 40 units battery	8,677,113.00	1.384	19,577,786.00	3.124
PV/wind/diesel system with 80 kW PV, 8 units wind turbine and 50 units battery	9,911,051.00	1.582	19,951,045.00	3.186

times from RM 8,484,458 to RM 24,041,486 and RM 1.353/kWh to RM 3.839/kWh, respectively. The incremental percentage is the highest as compared to other systems because the diesel only system greatly depends on the usage of fossil fuel. When the price of diesel increases, the annual cost and cost of energy of the system will increase proportionally. The percentage of increment for the NPC and the COE values of PV–diesel system with battery and PV–wind–diesel system with battery is 2.26% and 2%, respectively. Therefore, when the diesel price is extremely higher than usual, especially for those in remote areas, the options of PV/diesel/battery system and PV/wind/diesel/battery system can be benefited in terms of net present cost and cost of energy as compared to the stand-alone diesel system. At the same time, the fuel consumption and the emission of CO_2 could also be reduced for these systems.

7. Conclusion

The HOMER software has simulated 200 different configurations of hybrid renewable energy systems with diesel prices of RM 1.75/L and RM 7/L. The studied energy systems include stand-alone diesel system, PV/diesel system with and without battery, wind/diesel system with and without battery, and PV/wind/diesel system with and without battery. The diesel only system provides the lowest cost of energy (RM 1.353/kWh), yet it emits about 350 tons of CO_2 gas every year. It causes many environment problems in a long term view. The wind diesel system is not a good option in Johor Bahru because of the low wind speed and it may not be viable at all sites. Both PV/diesel system with 80 kW PV and 40 units battery and PV/wind/diesel system with 80 kW PV, 8 units wind turbine and 50 units battery performed well to reduce the dependence on solely available diesel resource. Although, the NPC and the COE values of these systems are higher than that of diesel only system, they can significantly reduce the fuel consumptions. In addition, these systems help to reduce the emission of CO_2 gasses of approximately 30% and 34.5% respectively. It results in the reduction of green house effect. Other than that, these systems would be more economical and cost-effective if the price of diesel increased significantly. In conclusion, the combination of PV and wind energy can supply continuous power to the load since the wind energy may not be viable at all sites due to its low wind speed and its unpredicted characteristics, while the solar energy can only supply power to load during daytime. The configuration of PV/wind/diesel/battery (80 kW PV, 8 units wind turbines and 50 units batteries) system has great potential to replace the stand-alone diesel system in Johor Bahru, Malaysia, since it provides reasonable cost of energy and cost of system installation, and in addition also significantly reduces the emission of CO_2 gasses.

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